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Abstract

In human infants trichromatic vision is functional within the first few months of life. Infants also make categorical responses to color – appearing to group together similar colors, but with distinct boundaries. Recent developments have revealed a candidate neural basis for infant color categories – the low-level cone-opponent mechanisms of color vision. These pre-linguistic boundaries appear to drive infant looking behavior, and may provide discontinuity in color perception around which linguistic color categories are formed in adults. This finding opens up new avenues for research, such as the need to understand how color categorization develops from being based on the low-level mechanisms of color vision in infancy to reflecting the linguistic, cultural and visual environment of the individual.

Highlights

Infants show categorical responding to color from a young age.

There are similarities between infant categories and the world's color lexicons.

Infant categorization appears to be driven by low-level color mechanisms.

Introduction

Color is experienced as a continuous stimulus feature, and the human visual system enables fine discrimination to be made between many similar colors. Yet, when we talk about color we tend to use a relatively limited number of "basic color terms" to refer to regions of color space [1]. Each of these regions contains many discernible colors which all can be communicated using the same linguistic label.

The World Color Survey (WCS) [1] characterized the color categories in use across 110 non-industrialized languages. The WCS found that the number of basic color terms varies from as few as two (one term for all "light" colors and one for "dark") to 11 or more (e.g. English: white, black, grey, red, orange, yellow, green, blue, purple, brown, pink). Speakers of languages with intermediate numbers of basic color terms tend to join what are adjacent categories in English into super-categories, for example using a single term to refer to all colors in the "red" and "orange" regions of color space. Despite the variation in number of basic color terms the position of the category boundaries show a surprising consistency across languages [2]. Therefore, despite the continuous nature of color perception, and infinite number of ways in which color space could be divided up for the purposes of linguistic categorization, there appear to be fault lines in color space at which category boundaries are more likely to develop. Where do these fault lines come from? One primary candidate is the visual system itself – is there something about the neural pathways encoding color that provides natural discontinuity upon which linguistic categorization is structured? Infant studies have particular power to shed light on the role that visual experience plays in the development of the neural pathways responsible for interpreting visual signals, and how cognitive and linguistic development scaffolds perceptual experience and cognitive processes. In this article we will review the most recent advances in the understanding of categorical color perception in infants, and we will discuss how these findings bear on these questions. Finally, we will discuss how taking account of environmental statistics of color may help shed more light on the developmental trajectory from infant to adult color categories.

Infant color vision & categorization

At birth, human infants have limited color vision, which rapidly develops in the first weeks of life. At first, the cone photoreceptors in the retina are morphologically immature [3] and organization of the fovea continues up to around 15 months of age [4]. Visual-evoked potentials reveal that color signals from the long- and medium-wavelength sensitive cones (serving the L/(L+M) cone-opponent sub-system of color vision) reach the cortex from 4 weeks [5] and from the short-wavelength sensitive cones (serving the S/(L+M)) around the same time [6]. Others have estimated a later functional onset for the S-cone subsystem [7]. Chromatic thresholds decline rapidly over the first few months [8] and infants show behavioral responses to chromatic stimuli at two months [9] and spontaneous color preferences by three months of age [10].

Many behavioral infant studies use habituation, novelty preference, and/or preferential looking to investigate the perception and encoding of stimuli (see figure 1). Habituation describes a steady decline in attention shown to a stimulus over repeated presentations. This technique is often used in tandem with novelty preference. After habituation infants prefer to look at something new, rather than the habituated stimulus. Looking time can be used to measure preference for a singleton target, and the direction of looking can be used for two-alternative forced-choice (2AFC) designs. Using this technique, Bornstein, Kessen & Weiskopf [11] claimed that infants respond categorically to blue, red, yellow and green at just 4 months, although the study has been criticized for stimulus limitations.

Similarly, Franklin and Davies [12] found novelty preferences in infants (4-6 months) dividing green from blue, blue from purple and pink from red. Event-related potentials (ERP) have also been used to demonstrate infants' categorical response to color at 7 months, revealing differences in ERP components related to attentional allocation [13]. Importantly, in these and other infant studies in this review, the infants taking part are pre-linguistic – they do not yet produce language nor show comprehension of color terms [14]. This assumption has never been directly addressed in the literature, for example with cross-cultural comparisons of infant categorization. Nevertheless, the available data does provide good evidence for infants' categorical response to color, prior to the production and comprehension of language, but the mechanism underlying these responses has remained unknown.

Recent advances

It appears that, even before acquiring language, infants have a tendency to divide the color space into categories. Important recent advances have taken place that further characterize infant color categories, seeking a fuller picture of where infants' categories fall, what neural mechanisms might underpin them, and which regions of the infant brain are involved in making categorical distinctions from continuous color information.

Yang, Kanazawa, Yamaguchi and Kuriki [15] sought to investigate categorical color encoding in the brains of infants aged 5 to 7 months, using near infra-red spectroscopy (NIRS). NIRS is a neuroimaging technique which provides an indication of functional brain activity derived from measured changes in cortical blood flow and oxygenation. A set of light sources and detectors is fitted close onto the head, usually with a cap or band holding them in place. Each light source emits a light in a narrow band in the near-infrared region of the electromagnetic spectrum, which is transmitted through the skull and reflects off the cortical surface of the brain. The spectral composition of the light which returns to the detector depends on the blood volume and oxygenation in that part of the brain. NIRS has several characteristics making it particularly suited to infant experiments. It is non-invasive, does not require extensive preparation of the participant or the environment, is relatively portable, and doesn't require the participant to stay in any particular position. Furthermore, due to infants' thinner hair, skin and skull, the quality of the NIRS signal from an infant participant is usually better than that from an adult participant [16]. Yang and colleagues [15] displayed to infants a set of different shapes on a screen. The color of the shapes changed every one second, alternating between two colors. During same-category trials, both colors were from the same (adult) color category – either both "blue" (B1-B2) or both "green" (G1-G2). In the different-category trials the two colors straddled the blue-green boundary (B1-G1). Trials for each category condition were interleaved with an achromatic baseline condition, in which the shapes appeared grey throughout but changed location every one second. The color pairs were approximately matched in perceptual difference by equating the Euclidean distance between them in CIE (1976) L*a*b*, a color space which attempts to approximate perceptual uniformity by accounting for some of the non-linearities in color perception (albeit based on adult, rather than infant, perception) [17]. Yang and colleagues found significant activation in the occipitotemporal (OT) cortex, bilaterally, in response to the different-category (B1-G1) trials, relative to the baseline, but not in response to the same-category (B1-B2/G1-G2) trials.

Yang's study was the first published attempt to localize category effects in the infant brain but the categorical effect was revealed only in the signal averaged across all 12 channels covering the OT region of each brain hemisphere. In summary, this study confirms the presence of categorical encoding albeit within a rather coarse region of the brain. It is tempting to assume that this means

that categorical response to color starts in early visual areas and is part of the representation of the world in the ventral stream as a result. However, it is also possible that the categorical activity in OT could be the result of top-down modulation from frontal regions, which have been implicated in categorical encoding of color in adults [18].

Another recent advance in our understanding of infant color categories was reported by Skelton, Catchpole, Abbott, Bosten and Franklin [19]. They used the habituation-novelty preference paradigm of Franklin and Davies [12] (see figure 1) to investigate hue categories in infants aged 4-6 months, sampling from the Munsell colors used in the WCS [1]. The Munsell Color System is intended to approximate perceptual differences across the color space (for a typical adult observer), such that by changing by one Munsell hue unit in blue is approximately perceptually equivalent to a one Munsell hue unit change in yellow. Skelton et al.'s study represents a much finer sampling of the color space than had been previously attempted (e.g. [12]). Rather than investigating particular *apriori* "boundaries" based on adult naming, their stimulus set was based on color pairs which were evenly spaced in Munsell hue and created a full hue circle around which to observe the continuity and discontinuity of infant novelty preference. Their results, from a sample of 179 infants, revealed that infants categorize colors into five main groups, within which they showed no novelty preference. Those groups correspond to what an English speaker might call "yellow", "green", "blue", "purple" and "red". The position of the infant category boundaries – defined by a significant novelty preference for a pair of colors – coincided with low incidence of category centroids (the Munsell color chosen as the best example of each color category in the language of the speaker) across the 110 non-industrialized languages in the WCS. In short this showed that the way that infants categorize color corresponds well with the commonalities across languages – suggesting that infant categories could partially provide fault lines around which lexical terms for colors can develop.

But what is the source of those fault lines in infancy? What mechanisms could account for them? Firstly, it might be that the stimulus space is uneven, the categorical "boundaries" might be points where the perceptual difference between the colors is greater, so the response is driven not by categorization but perceptual difference. Since the infant data and the World Color Survey are based on the same stimulus set this could also explain the concordance of the results between the two. Skelton and colleagues addressed this by testing color pairs which were more different – and confirmed that novelty preference was consistently absent within the categories identified initially, and was consistently present across much smaller color differences which crossed a category boundary. They then observed that when plotted on the MacLeod-Boynton chromaticity diagram [20], four out of the five infant hue category boundaries occurred at, or very close to, the points where the stimulus colors spanned the cardinal axes through the achromatic point (figure 2). Those cardinal axes represent the activations, relative to the adaptation point, of the two sub-systems of trichromatic primate vision – the L/(L+M) and S/(L+M) retinogeniculate mechanisms, which represent the low-level neural coding of color information. A fifth category, separating yellows from reds, did not fit this pattern. The presence of this additional fault line in infant hue space is evidence that the cardinal mechanisms of color vision are not solely responsible for categorization at this age, and other factors both learned (e.g. environmental factors) and innate warrant further investigation.

Infants, therefore, appear to have some (although not all) hue categories based on the polarity of the signal from the early cone-opponent mechanisms. So, following habituation to a given color, an infant's looking will be oriented to a novel color if the novel color is of the opposite polarity in one or other of the cardinal color mechanisms compared to the habituated color (e.g. from an L/(L+M) increment to L/(L+M) decrement or *vice versa*). In naïve adult observers evidence for a link between cone-opponent mechanisms, perception and categorization is mixed. The poles of the cone-opponent

mechanisms are not consistently associated with enhanced discrimination [21], or unique hues (red, green, yellow and blue) [22] in adults (see [23] for a comprehensive review). The average binary hue settings of blue-green, yellow-green and red-blue may fall close to three of the cardinal axes, but the positive pole of the L/(L+M) axis is closer to unique red, rather than a categorical boundary [22], and the red-blue binary hue, although close to the positive pole of the S/(L+M) axis, is also close to typical "purple" for speakers of German and English [21, 24, 25] (i.e. not a color category boundary). Skelton et al. [19] demonstrated a resemblance between the clustering of category boundaries in the WCS and the infant boundaries they observed [19, figure 1], yet the existence of color naming systems with fewer than four hue categories (e.g. Wobé, a language with three basic color terms, only one of which designates a hue, the other two divide light from dark [1]) shows that these cone-opponent fault lines can be healed by language. Similarly language can cleave new boundaries which do not coincide with the cardinal axes (e.g. purple-blue boundary). The next challenge for the study of infant color categories is to understand this process of category maturation, from infant categories, where low-level coding dominates categorization, to adult categories, where language dominates categorization.

The perceptual uniformity of stimulus space is an issue for studies of infant categorization as it is for adult studies [26]. Measuring infant hue discrimination would prove a useful step forward in addressing this issue, allowing comparison to adult thresholds [21] and testing whether infant discrimination reflects infant categorization by being heightened around the cardinal axes of cone opponent space. The link between fine-grained perceptual discrimination and how color categories influence adult perception has been formalized in a probabilistic inference framework [27], the basis of which may help integrate the findings in color with the wider exploration of infant perception and categorization. Indeed, one study has drawn links between color categorization and face categorization, describing a transition from cognition led by perceptual discrimination to cognition led by categorization, the latter being the result of acculturation and environmental tuning [28]. The connection between color categories and the statistics of the environment is another area worthy of further exploration. Gibson et al. analyzed a database of photographs containing various natural and man-made objects in their usual context [29]. They found that objects tended to be warm colors, while backgrounds were dominated by cool colors. They proposed that this tendency may be reflected in the warm-cool categorical distinction, which is common across the world's color lexicons. Whether this particular statistical regularity in object-hue relationship applies to a wide range of cultural and environmental contexts remains an open question. Nevertheless the connection between categorization and environmental statistics generates a fascinating set of hypotheses to which infant data can be brought to bear. For example, if the infant brain is working to partition color space in a way which optimizes the communicability of environmentally relevant colors [30] then we should see variations in infant categories become increasingly attuned to the statistics of their environment, and particularly the objects with which they interact. This could also account for cross-linguistic variations in the timing of acquisition of different color terms [31] – cultural and geographical differences in the type and materials of items referred to by caregivers and with which the infant interacts may produce biases in the statistical distribution of colors. The infant brain is strongly disposed to statistical learning [32] and any such environmental variation could form the basis for the development of color categories.

Discussion

Infant studies provide a unique window into the visual system as it develops and allow us to chart the influence of the visual, cultural and linguistic environment on perception and cognition. Categorization appears to be a fundamental feature of how color is processed by the brain (for a comprehensive

review, see [33]), and is present in human infants from the first few months of life. The recent advances described in this review have provided yet more evidence of this, both behaviorally [19], and with measurements of brain activity [15]. We now have a plausible neural mechanism upon which some infant color categories might be based, namely the cone-opponent channels. At present there is no framework for understanding the way in which color processing progresses from the infant state, in which some categorical groupings are made by polarity of the cardinal color contrast mechanisms, to the adult-like state where categories are linguistically defined. There has been a recent attempt to bridge the gap between adult and infant color perception, investigating how hue, saturation and lightness interact to create saliency in 6-month-olds [34]. It should not be presupposed that those dimensions are a good description of infant perception, given the lack of evidence for such structure in adult perception [35-38] (see also [39] for an account of a historical color space based on quite different dimensions). Nevertheless, an approach investigating the dimensions of color perception in infants may facilitate more refined comparisons of infant and adult color perception and categorization.

Our review has identified some important advances in the study of infant color categorization in recent years, revealing some commonality between infant hue categories and the color categories of the world's languages. However, while infants appear to use low-level stimulus encoding as a basis for categorical responding, adult categories are not solely explainable in these terms. The challenge now lies in understanding how and when infant color categories mature, allowing the observer to re-partition color space according to the designations of the language they acquire, rather than the neural mechanisms responsible for low-level color processing.

Figures

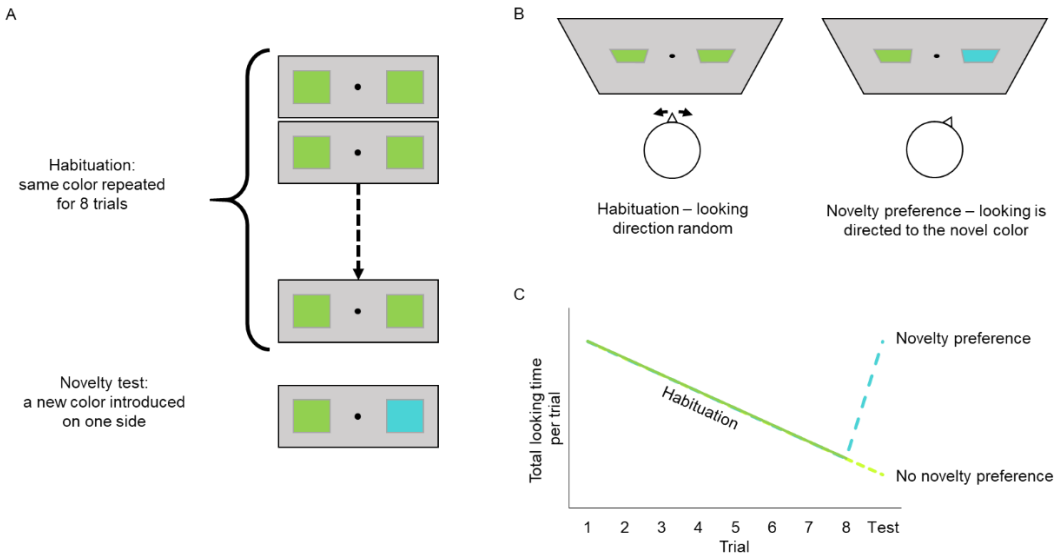

Figure 1: Infant two-alternative forced-choice (2AFC) habituation-novelty preference method, as used in [12, 19]. A) The same color is presented on both sides of the 2AFC array during habituation, which is repeated for 8 trials, each lasting 8 seconds. The novelty test involves introducing a new color to one of the locations. B) During habituation looking direction is expected to be randomly distributed between the two identical color patches. In the test trial a novelty preference is indicated by the infant orienting their looking to the novel color. A lack of novelty preference is shown if the infant continues to distribute their looking to both sides equally, even when the novel color is introduced. Looking direction and time is coded by video recorded from a camera positioned between the stimuli, facing the infant (black dot). The coder is blind to the stimulus arrangement. C) Habituation is indicated by an overall decline in looking at the repeated stimuli during the habituation trials. At test, one of two patterns is expected – either an increase in looking time (in addition to the directional effect shown in B) indicating novelty preference (blue line), or no novelty preference, in which looking time remains short (yellow line).

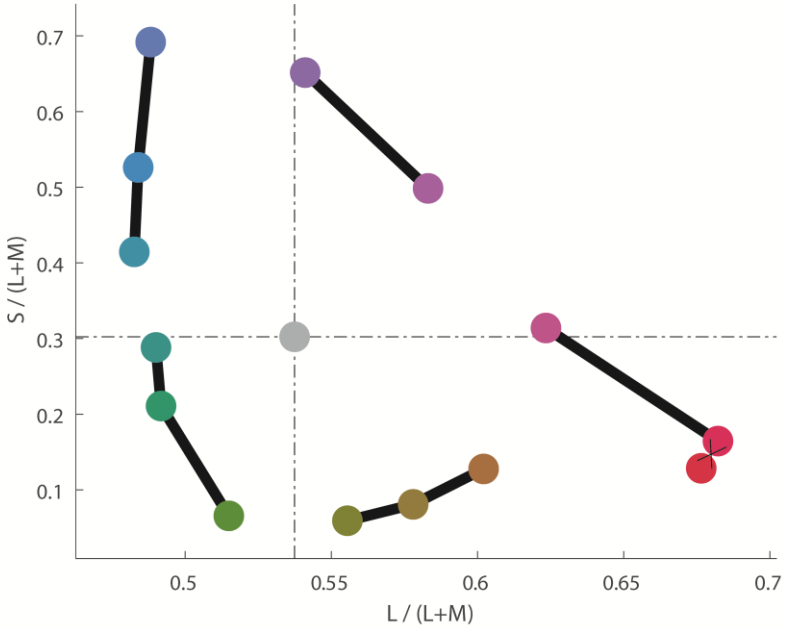

Figure 2: Re-plotting of data from [19], indicating the locations of infant color categories. The axes correspond to the retinogeniculate pathways in the Macloed-Boynton chromaticity diagram. The dot-dash line indicates the "cardinal axes" in terms of visual adaptation, passing through the achromatic point (filled grey circle) from that experiment. Filled circular points approximate the Munsell colors presented to infants. Thick black lines between adjacent colors indicate a lack of novelty preference, where there is no line between adjacent colors infants showed a novelty preference, indicating separate categories. Four of these five infant boundaries fall at, or very close to, where the cardinal axes pass through the space. The thin crossed lines indicate a pair which was not tested, all other adjacent pairs were tested.

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Conflict of interest

None declared.

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This paper follows the finding of [11], improving on the stimulus issues by using the Munsell color system. Using habituation and novelty preference, the authors show that 4-6 month-old infants categorize hue into at least four categories, and also there is evidence for lightness boundary separating red from pink.

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